

Spectropolarimetric Constraints on the Nature of Interstellar Grains

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ABSTRACT

While it is well recognized that interstellar grains are made of amorphous silicates and some form of carbonaceous materials, it remains debated regarding what exact chemical and physical form the carbonaceous component takes. Contemporary grain models assume that the silicate and carbon components are either physically separated, or they form a core-mantle structure, or they agglomerate to form porous composites. The core-mantle model posits that the mantle is made of some sort of aliphatic hydrocarbon materials and is responsible for the $3.4\,\mu\text{m}$ absorption feature ubiquitously seen in the diffuse interstellar medium (ISM) of the Milky Way and external galaxies. This model is challenged by the nondetection of polarization in the $3.4\,\mu\text{m}$ absorption feature as the $9.7\,\mu\text{m}$ silicate feature is observed to be polarized. To alleviate this challenge, we calculate the degree of polarization of the $3.4\,\mu\text{m}$ feature for *spheroidal* silicate dust coated by a layer of *spherical* aliphatic hydrocarbon. It is found that the $3.4\,\mu\text{m}$ feature polarization still exceeds the observational upper limit, even though *spherical* aliphatic hydrocarbon mantles are expected to cause much less polarization than *nonspherical* (e.g., spheroidal) mantles. We have also shown that the composite grain model which consists of amorphous silicate, aliphatic hydrocarbon, and vacuum also predicts the $3.4\,\mu\text{m}$ feature polarization to well exceed what is observed. These results support the earlier arguments that the aliphatic hydrocarbon component is physically separated from the silicate component unless the $3.4\,\mu\text{m}$ absorption feature is just a minor carbon sink in the ISM.

Key words: dust, extinction – infrared: ISM – polarization

1 INTRODUCTION

Although the exact nature of interstellar dust remains uncertain, it is now well recognized that interstellar grains consist of amorphous silicates and some form of carbonaceous materials. While the identification of amorphous silicate dust in the interstellar medium (ISM) is relatively secure through the broad featureless $9.7\,\mu\text{m}$ Si–O stretching and $18\,\mu\text{m}$ O–Si–O bending absorption features (see Henning 2010), our understanding of the carbon dust component, mainly through the $2175\,\text{\AA}$ extinction bump and the $3.4\,\mu\text{m}$ C–H absorption feature is not as clear.

All contemporary dust models assume carbon dust as a key grain component. They differ mainly in terms of the exact chemical and physical forms the carbon dust component take: (1) The silicate-graphite model (Mathis et al. 1977; Draine & Lee 1984; Siebenmorgen & Krügel 1992; Weingartner & Draine 2001; Draine & Li 2007) assume that graphite

is the major carbon sink and the silicate and graphite components are bare and physically separated; (2) The silicate core-carbonaceous mantle model (Désert et al. 1990; Jones et al. 1990; Li & Greenberg 1997; Jones et al. 2013) assumes that silicate grains are coated with a carbonaceous mantle made of either hydrogenated amorphous carbon (HAC) or organic refractory; (3) The composite model (Mathis & Whiffen 1989; Mathis 1996; Zubko et al. 2004) assumes the dust to be low-density aggregates of small silicates and carbonaceous particles (amorphous carbon, HAC, and organic refractories). All dust models appear to be in general agreement with the observational constraints, including the interstellar extinction, scattering, polarization, IR emission and interstellar depletion.

More recently, spectropolarimetry of the $3.4\,\mu\text{m}$ interstellar absorption feature has been used to distinguish between dust models (Adamson et al. 1999; Ishii et al. 2002; Chiar et al. 2006; Mason et al. 2007). The $3.4\,\mu\text{m}$ absorption feature, commonly attributed to the C–H stretching mode in saturated aliphatic hydrocarbon dust (see Pendleton &

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Allamandola 2002), is ubiquitously seen in the diffuse ISM of the Milky Way and external galaxies (e.g., see Mason et al. 2004).¹

The silicate core-carbonaceous mantle model assumes that the 3.4 μm absorption feature arises in the hydrocarbon mantles coating the amorphous silicate cores (Jones et al. 1990; Li & Greenberg 1997). The hydrocarbon mantles consist of either “organic refractory” (Greenberg et al. 1995) or HAC (Jones et al. 1990). Both “organic refractory” and HAC provide a close match to the interstellar 3.4 μm absorption feature (Greenberg et al. 1995; Mennella et al. 1999). The interstellar organic refractory material is essentially HAC in character. The major difference between the organic refractory material with HAC lies in the way how they are made: the former is derived from the UV photo-processing of interstellar ice mixtures accreted on the pre-existing silicate cores (Greenberg et al. 1995); the latter results from direct accretion of gas-phase elemental carbon on the silicate cores in the diffuse ISM (Duley et al. 1989; Jones et al. 1990).

The 9.7 μm and 18 μm silicate absorption features have been reported to be polarized along various sightlines probing both the diffuse ISM and dense molecular clouds (see Smith et al. 2000, Wright et al. 2002, Aitken 2005), suggesting that the silicate component is nonspherical and aligned. If the carrier of the 3.4 μm feature resides in the carbonaceous mantles on the silicate cores, we would expect the 3.4 μm absorption feature to be polarized as well (see Li & Greenberg 2002).

However, all spectropolarimetric observations show that the 3.4 μm absorption feature is essentially unpolarized (Adamson et al. 1999, Ishii et al. 2002, Chiar et al. 2006, Mason et al. 2007). This, especially the nondetection of the 3.4 μm feature polarization in the Galactic center Quintuplet combined with the fact that the 9.7 μm silicate feature is polarized in the same sightline (Chiar et al. 2006), poses a severe challenge against the core-mantle model. They argue that the hydrocarbon dust do not reside on the same grains as the silicates, and likely form a separate population of small grains which are either spherical or not sufficiently aligned.

This challenge might be alleviated if the mantle is much less elongated than the silicate core so that the 3.4 μm feature would be polarized to a much smaller degree than the 9.7 μm silicate feature. The aim of this work is to investigate this scenario. We consider an extreme case: the dust consists of a *spheroidal* silicate core coated with a layer of *spherical* aliphatic hydrocarbon mantle (§2). To be complete, we also consider the composite model in §3. We discuss these results in §4.

2 SPHEROIDAL CORE-SPHERICAL MANTLE DUST

Interstellar polarization is caused by the differential extinction of the 2 perpendicular electric vectors of starlight by aligned, nonspherical grains. The less elongated the carrier

of the 3.4 μm feature is, the less is the degree to which the 3.4 μm feature will be polarized. Therefore, a lower limit on the 3.4 μm absorption polarization will be achieved if the hydrocarbon mantles are *spherical*, while the silicate cores are *elongated*. We therefore consider *spheroidal* silicate core-*spherical* carbonaceous mantle grains.

Let a_c and b_c be the core semi-axis along and perpendicular to the symmetry axis respectively; r be the spherical radius of the mantle. Let V_{sil} and V_{carb} be the silicate core and carbonaceous mantle volumes, respectively. The mantle-to-core volume ratio: $V_{\text{carb}}/V_{\text{sil}} = (r^3 - a_c b_c^2)/a_c b_c^2$ can be estimated from the observed optical depths of the 3.4 μm hydrocarbon feature ($\tau_{3.4}$) and the 9.7 μm silicate feature ($\tau_{9.7}$): $V_{\text{carb}}/V_{\text{sil}} \approx (\tau_{3.4}/\tau_{9.7}) (\rho_{\text{sil}}/\rho_{\text{carb}}) (\kappa_{\text{sil}}^{9.7}/\kappa_{\text{carb}}^{3.4}) \approx 0.25$ where $\tau_{3.4}/\tau_{9.7} \approx 1/18$ (Sandford et al. 1995); ρ_{sil} and ρ_{carb} are the mass densities of the silicate ($\approx 3.5 \text{ g cm}^{-3}$) and carbonaceous dust ($\approx 1.5 \text{ g cm}^{-3}$); $\kappa_{\text{sil}}^{9.7}$ is the 9.7 μm Si-O silicate mass absorption coefficient ($\approx 2850 \text{ cm}^2 \text{ g}^{-1}$; Draine & Lee 1984); $\kappa_{\text{carb}}^{3.4}$ is the 3.4 μm C-H mass absorption coefficient of carbonaceous organic refractory dust ($\approx 1500 \text{ cm}^2 \text{ g}^{-1}$; see Li & Greenberg 2002). However, a much thicker mantle ($V_{\text{carb}}/V_{\text{sil}} \approx 1$) is required to account for the visual/near-IR interstellar extinction (Li & Greenberg 1997). The mass ratio of carbonaceous organics to silicates in the coma of comet Halley, measured *in situ*, was approximately 0.5 (Kissel & Krueger 1987), pointing to $V_{\text{carb}}/V_{\text{sil}} \approx 1$. It is often suggested that cometary dust is made of interstellar grain aggregates (Greenberg & Li 1999, Kimura et al. 2003, Kolokolova & Kimura 2010). In dense clouds we would expect a thicker hydrocarbon mantle (although the 3.4 μm feature is not seen in dense molecular clouds; see Mennella et al. 2001, Mennella 2010). Therefore, we will consider 3 mantle thicknesses: $V_{\text{carb}}/V_{\text{sil}} = 0.25, 1, 2$. If the available Si elements (say, ≈ 32 ppm per H atom like that of Sun where ppm refers to parts per million; Asplund et al. 2009) are all depleted in the silicate cores, the carbonaceous mantles require C/H $\approx 49, 196, 392$ ppm. Given the interstellar abundance constraints (e.g. see Li 2005), $V_{\text{carb}}/V_{\text{sil}} < 1$ seems more reasonable. We consider a wide range of core-elongations of a_c/b_c which are required to satisfy the constraint of $V_{\text{sil}}/(V_{\text{carb}} + V_{\text{sil}}) < a_c/b_c \leq [(V_{\text{carb}} + V_{\text{sil}})/V_{\text{sil}}]^{1/2}$ since both a_c and b_c must be smaller than r .

Let $C_{\text{abs}}^{\parallel}$ and C_{abs}^{\perp} be the absorption cross sections for light polarized parallel and perpendicular, respectively, to the grain symmetry axis. For an ensemble of grains spinning and precessing about the magnetic field, the polarization cross section is $C_{\text{pol}}^{\text{pro}} = (C_{\text{abs}}^{\parallel} - C_{\text{abs}}^{\perp})/2$ for prolates, and $C_{\text{pol}}^{\text{obl}} = (C_{\text{abs}}^{\perp} - C_{\text{abs}}^{\parallel})$ for oblates; the absorption cross section is $C_{\text{abs}} = (C_{\text{abs}}^{\parallel} + 2C_{\text{abs}}^{\perp})/3 - \Phi C_{\text{pol}} (3 - 2/\cos^2 \gamma)/6$ where Φ is the polarization reduction factor; γ is the angle between the magnetic field and the plane of the sky (Lee & Draine 1985). We take $\Phi = 1$ and $\gamma = 0$.

For a given core-elongation of a_c/b_c and a given mantle-to-core volume ratio of $V_{\text{carb}}/V_{\text{sil}}$, we use the discrete dipole approximation of Draine (1988; DDSCAT) to calculate the 3.4 μm C-H excess extinction $A_{3.4}$ and excess polarization $P_{3.4}$, as well as the 9.7 μm Si-O excess extinction $A_{9.7}$ and excess polarization $P_{9.7}$. Here by “excess” we mean the extinction and polarization of the absorption feature in excess of the continuum extinction and polarization under-

¹ Chiar et al. (2013) argued that the carrier of the 3.4 μm feature is largely aromatic instead of aliphatic. But see Dartois et al. (2007) who argued that the carrier of the 3.4 μm feature is highly aliphatic.

neath the feature. In Figure 1 we show the polarization-to-extinction ratio as a function of core-elongation a_c/b_c for 3 different mantle thicknesses $V_{\text{carb}}/V_{\text{sil}} = 0.25, 1, 2$ for the $9.7\ \mu\text{m}$ silicate feature, the $3.4\ \mu\text{m}$ hydrocarbon feature, and the visible band (P_V/A_V). Also shown in Figure 1 is $(P_{3.4}/A_{3.4})/(P_{9.7}/A_{9.7})$, which measures the degree to which the $3.4\ \mu\text{m}$ hydrocarbon feature is polarized relative to the $9.7\ \mu\text{m}$ silicate feature.

As expected, the more elongated the core is, the more polarized is the $9.7\ \mu\text{m}$ silicate feature (see Figure 1a). This is also true for the $3.4\ \mu\text{m}$ hydrocarbon feature (see Figure 1b) and the visible band (see Figure 1c). This can be understood from the grain geometry: for grains with a prolate (oblate) core, the light polarized along the semi-minor (semi-major) axis will see more hydrocarbon dust. Therefore, the more elongated the core is, the larger is the difference between the extinction of starlight polarized along the semi-major axis and that along the semi-minor axis.

The mantle thickness has little effect on the silicate feature polarization (see Figure 1a). But for the $3.4\ \mu\text{m}$ hydrocarbon feature, it becomes less polarized when the mantle becomes thicker (see Figure 1b). This is not unexpected – when the mantle becomes thicker, the difference between the amounts of hydrocarbon dust seen by the two electric vectors of starlight becomes smaller. If the spherical mantle is very thick (i.e. $V_{\text{carb}} \gg V_{\text{sil}}$), the $3.4\ \mu\text{m}$ feature will become essentially unpolarized.

As expected from a combination of Figure 1a and Figure 1b, the relative polarization $(P_{3.4}/A_{3.4})/(P_{9.7}/A_{9.7})$ decreases as the silicate cores are more elongated (see Figure 1d); it also decreases as the hydrocarbon mantle becomes thicker.

3 COMPOSITE MODEL

We now consider the composite dust model in which interstellar grains are taken to be fluffy aggregates of small silicates, vacuum, and carbon of various kinds (amorphous carbon, HAC, and organic refractories; Mathis & Whiffen 1989, Mathis 1996). We test this model using DDSCAT and assuming the composite grains are spheroidal-shaped.

Following Mathis (1996), we take the volume-filling factor of vacuum $f_{\text{vac}} = 0.45$, and the mass ratio between hydrocarbon dust and silicate dust $m_{\text{carb}}/m_{\text{sil}} = 0.7$. The volume-filling factor is $f_{\text{sil}} \approx 0.21$ and $f_{\text{carb}} \approx 0.34$ for the silicate component and the hydrocarbon component, respectively (i.e., $V_{\text{carb}}/V_{\text{sil}} \approx 1.62$).

Let $\kappa_{\text{abs}}(3.4)$ and $\kappa_{\text{abs}}(9.7)$ respectively be the mass-absorption coefficient of the $3.4\ \mu\text{m}$ feature and the $9.7\ \mu\text{m}$ feature in excess of the continuum. For composite grains, we use DDSCAT to calculate $\kappa_{\text{abs}}(3.4)$ and $\kappa_{\text{abs}}(9.7)$ and derive $\kappa_{\text{abs}}(3.4) \approx 240\ \text{cm}^2\ \text{g}^{-1}$ and $\kappa_{\text{abs}}(9.7) \approx 1500\ \text{cm}^2\ \text{g}^{-1}$, independent of elongation.

We calculate the polarization-to-extinction ratio as a function of elongation $a/b = 0.1 - 10$. As shown in Figure 2, $(P_{3.4}/A_{3.4})/(P_{9.7}/A_{9.7}) \approx 1.02 - 1.08$. We have also calculated the polarization-to-extinction ratio for composite dust using the Bruggeman effective medium theory (see Bohren & Huffman 1983). The results are very close to that calculated from DDSCAT, only differing by $< 2\%$ (see Figure 2). We conclude that the composite model predicts a similar degree of polarization (i.e., $P_{9.7}/A_{9.7} \approx P_{3.4}/A_{3.4}$) for the $9.7\ \mu\text{m}$

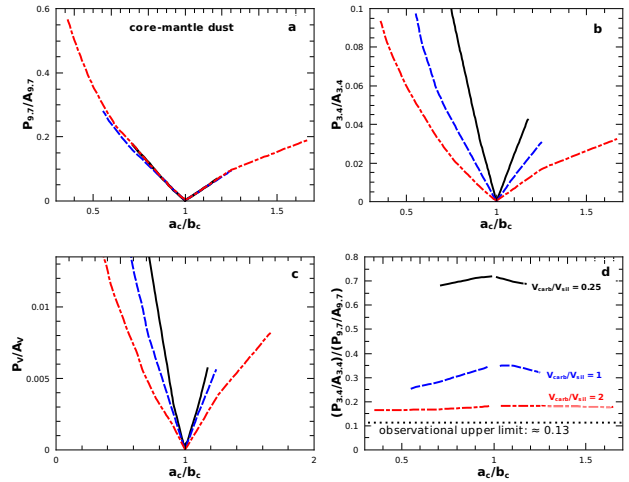


Figure 1. Polarization-to-extinction ratios of (a) the $9.7\ \mu\text{m}$ silicate feature $P_{9.7}/A_{9.7}$, (b) the $3.4\ \mu\text{m}$ hydrocarbon feature $P_{3.4}/A_{3.4}$, and (c) the visible band P_V/A_V , as well as (d) the relative polarization $(P_{3.4}/A_{3.4})/(P_{9.7}/A_{9.7})$, predicted from the spheroidal silicate core-spherical hydrocarbon mantle model as a function of core-elongations (a_c/b_c) for 3 mantle thicknesses $V_{\text{carb}}/V_{\text{sil}} = 0.25$ (solid), 1 (dashed), and 2 (dot-dashed). In panel (d) the lines break at $a_c/b_c = 1$ since $P_{9.7}/A_{9.7} = 0$ and $P_{3.4}/A_{3.4} = 0$ for dust with $a_c/b_c = 1$ (i.e., spherical dust does not cause polarization). Also shown in panel (d) is the upper limit of $(P_{3.4}/A_{3.4})/(P_{9.7}/A_{9.7}) \approx 0.13$ (dotted) observed for the $3.4\ \mu\text{m}$ feature polarization of the Galactic center Quintuplet object GCS 3-II (Chiar et al. 2006).

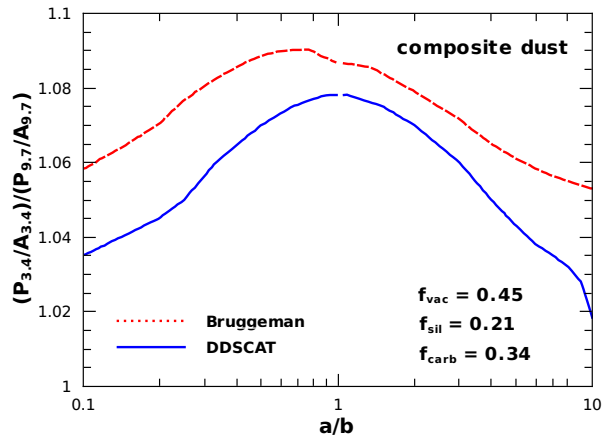


Figure 2. Relative polarization $(P_{3.4}/A_{3.4})/(P_{9.7}/A_{9.7})$ predicted from the composite model (with $V_{\text{carb}}/V_{\text{sil}} \approx 1.62$) as a function of elongations of a/b in the range of $0.1 < a/b < 10$ (except $a/b = 1$ for which $P_{9.7}/A_{9.7} = 0$ and $P_{3.4}/A_{3.4} = 0$).

Si–O feature and the $3.4\ \mu\text{m}$ C–H feature, implying that the composite model is also inconsistent with the nondetection of $3.4\ \mu\text{m}$ C–H polarization feature.

4 DISCUSSION

Since the spheroidal core-spherical mantle grains considered in §2 represent an extreme case in which the $3.4\ \mu\text{m}$ hydrocarbon feature is least polarized (relative to the $9.7\ \mu\text{m}$ silicate feature), if in an astronomical object the $3.4\ \mu\text{m}$ absorption feature is observed to have an even lower degree

of polarization, the core-mantle model will be severely challenged.

Chiar et al. (2006) placed an upper limit on the $3.4\ \mu\text{m}$ feature polarization of the Galactic center Quintuplet object GCS 3-II: $(P_{3.4}/A_{3.4})/(P_{9.7}/A_{9.7}) \approx 0.13$. This upper limit is even lower than the lower limits predicted from the spheroidal core-spherical mantle model with $V_{\text{carb}}/V_{\text{sil}} = 2$ for which $(P_{3.4}/A_{3.4})/(P_{9.7}/A_{9.7}) > 0.16$ (see Figure 1d) over the entire allowable ranges of core-elongations ($1/3 < a_c/b_c < \sqrt{3}$; see §2). This supports the idea put forward by Adamson et al. (1999) and Chiar et al. (2006) that, based on the nondetection of the $3.4\ \mu\text{m}$ feature polarization, the core-mantle model is invalid or the carrier of the $3.4\ \mu\text{m}$ feature does not reside in the carbonaceous mantle as previously thought. The hydrocarbon dust component responsible for the $3.4\ \mu\text{m}$ feature must be physically separated from the silicate component. This component must be either spherical or poorly aligned (or both) so that the resulting $3.4\ \mu\text{m}$ absorption feature is essentially unpolarized.

With a *thicker* carbon mantle, one expects a *smaller* $3.4\ \mu\text{m}$ polarization-to-extinction ratio $P_{3.4}/A_{3.4}$. With $V_{\text{carb}}/V_{\text{sil}} > 3$, we obtain $(P_{3.4}/A_{3.4})/(P_{9.7}/A_{9.7}) < 0.13$ which appears to satisfy the observational upper limit of Chiar et al. (2006). However, grains with such a thicker spherical mantle would produce little polarization in the optical wavelength range. This is inconsistent with the observations of the interstellar polarization: (1) light reaching us from reddened stars is often polarized in the optical; (2) the interstellar polarization curve — the degree of polarization as a function of wavelength — rises from the near-IR ($\lambda \sim 2\ \mu\text{m}$), has a maximum somewhere in the optical ($\lambda_{\text{max}} \approx 0.55\ \mu\text{m}$) and then decreases toward the ultraviolet (UV; see Whittet 2003). To be considered successful, a grain model should have its bulk, submicrometer-sized dust component to be non-spherical and sufficiently aligned to reproduce the observed interstellar polarization curve (e.g., see Voshchinnikov 2012). The silicate-graphite model requires either silicate (e.g., Mathis et al. 1977, Kim & Martin 1994) or both silicate and graphite (see Draine & Fraisse 2009, Siebenmorgen et al. 2014) to account for the observed optical polarization. The core-mantle model requires the core-mantle dust to produce the interstellar optical polarization (see Li & Greenberg 1997). The composite model requires the porous composite dust to account for the observed optical polarization (see Mathis & Whiffen 1989, Mathis 1998).

We note that, as shown in Figure 1c, with $V_{\text{carb}}/V_{\text{sil}} > 1$, the optical polarization-to-extinction ratio (P_V/A_V) predicted from the spheroidal core-spherical mantle model is too small to compare with the observational value of $P_V/A_V \leq 0.064$ (Whittet 2003) which should be achieved for perfectly aligned grains. This indicates that, although with a thick spherical carbon mantle one may satisfy the observed upper limit of $(P_{3.4}/A_{3.4})/(P_{9.7}/A_{9.7}) < 0.13$, the starlight will essentially see the dust as *spherical* and will not be polarized in the optical.

The composite model is not able to alleviate the $3.4\ \mu\text{m}$ polarization challenge. With $(P_{3.4}/A_{3.4})/(P_{9.7}/A_{9.7}) \approx 1.02 - 1.08$ (compared with the observed upper limit of $(P_{3.4}/A_{3.4})/(P_{9.7}/A_{9.7}) \approx 0.13$; Chiar et al. 2006), the composite model predicts a similar degree of polarization for the $9.7\ \mu\text{m}$ Si–O feature and the $3.4\ \mu\text{m}$ C–H feature. This indicates that the $3.4\ \mu\text{m}$ hydrocarbon feature should have a pos-

itive detection for the lines of sight along which the $9.7\ \mu\text{m}$ silicate feature is observed to be polarized. The nondetection of the $3.4\ \mu\text{m}$ feature polarization in the Galactic center Quintuplet combined with the detection of the $9.7\ \mu\text{m}$ silicate feature polarization in the same sightline (Chiar et al. 2006) poses a severe challenge against the composite model.

The core-mantle model may remain valid if the mantle component does not contain the carrier of the $3.4\ \mu\text{m}$ absorption feature, i.e., the carrier of the $3.4\ \mu\text{m}$ absorption feature is not a major carbon sink in the ISM and is physically not associated with the bulk core-mantle dust. Jones et al. (2013) argued that the aliphatic hydrocarbon material is subject to UV photo-processing in the diffuse ISM and is expected to be maximally-aromatized in the order of a million years. Therefore, they suggested that the mantle material of the core-mantle dust is mainly aromatic and is not responsible for the $3.4\ \mu\text{m}$ absorption feature. According to Jones et al. (2013), the $3.4\ \mu\text{m}$ absorption feature is due to a separate population of small aliphatic hydrocarbon dust.

If the core-mantle dust is not responsible for the $3.4\ \mu\text{m}$ absorption feature, we might encounter a carbon budget problem: if the total carbon abundance (relative to H) in the ISM is like the Sun $[C/H]_{\text{ISM}} = [C/H]_{\odot} \approx 224\ \text{ppm}$ (Asplund et al. 2009)² or proto-Sun $[C/H]_{\text{ISM}} = [C/H]_{\odot} \approx 288\ \text{ppm}$ (Lodders 2003), with $[C/H]_{\text{gas}} \approx 140\ \text{ppm}$ in the gas phase (Cardelli et al. 1996) and $[C/H]_{\text{PAH}} \approx 60\ \text{ppm}$ in PAHs (Li & Draine 2001) subtracted, there is only $[C/H]_{\text{dust}} \approx 24\ \text{ppm}$ or $[C/H]_{\text{dust}} \approx 57\ \text{ppm}$ left for the $2175\ \text{\AA}$ extinction bump, the $3.4\ \mu\text{m}$ absorption feature, the “extended red emission” (ERE) which is most likely from some sort of small carbon-based dust (Witt & Vijh 2004), and a population of bulk carbon dust.³ The latter is required to account for part of the visual extinction since silicates alone are not able to provide enough extinction (see Footnote-14 in Li 2004).

Furthermore, according to Draine (1990) and Jones et al. (1994), most of the dust mass in the ISM was condensed in the ISM, it is not very clear how it is possible for the recondensation to keep the silicate and carbon grain populations apart in the ISM. Draine (2009) postulated a scenario for the ISM to grow two distinct grain types (i.e., silicate and carbon dust) out of a single gas mixture. He argued that when Mg, Si, Fe, and O atoms and ions arrive at the amorphous silicate surface, they are able to grow additional amorphous silicate; in contrast, the C atom physisorbed on the amorphous silicate surface might undergo photoexcitation to an excited state that is repulsive, ejecting it from

² We note that the C abundance of the early B stars which are thought to be ideal indicators for the present-day interstellar abundances since they preserve their pristine abundances is close to the solar C abundance: $[C/H]_{\star} \approx 214 \pm 20\ \text{ppm}$ (Przybilla et al. 2008) and $[C/H]_{\star} \approx 209 \pm 15\ \text{ppm}$ (Nieva & Przybilla 2012).

³ Sofia et al. (2011) derived $[C/H]_{\text{gas}} \approx 100\ \text{ppm}$ for several interstellar sightlines from the strong transition of C II] at $1334\ \text{\AA}$. They argued that the oscillator strength for the C II] transition at $2325\ \text{\AA}$ previously used by Cardelli et al. (1996) to obtain $[C/H]_{\text{gas}} \approx 140\ \text{ppm}$ might have been underestimated. But even with $[C/H]_{\text{gas}} \approx 100\ \text{ppm}$, the amount of C available for the $2175\ \text{\AA}$ bump, the $3.4\ \mu\text{m}$ feature, the ERE, and the bulk carbon dust, is only $[C/H]_{\text{dust}} \approx 64\ \text{ppm}$ or $[C/H]_{\text{dust}} \approx 97\ \text{ppm}$ and does not seem to be sufficient.

the surface. Or perhaps the C would become hydrogenated or oxidized, with the resulting CH or CO undergoing photodesorption from the surface. Such processes could keep the amorphous silicate carbon-free in the diffuse ISM. Similar processes may occur on exposed carbonaceous surfaces: impinging C atoms could grow new carbonaceous material, whereas impinging Mg, Si, Fe atoms could be removed by some combination of reaction with impinging H or O, and photoexcitation by UV.

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